SQUID-based Readout Schemes for Microcalorimeter Arrays

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Abstract. Microcalorimeter arrays with superconducting phase-transition thermometers are an attractive alternative for construction of imaging X-ray spectrometers. The low source impedance and low operating temperatures make dc SQUIDs good candidates for their preamplifiers. In large arrays, the circuit complexity as well as heat leakage through wiring make some sort of a multiplexing scheme desirable. Some circuit topologies for time-domain and frequency-domain multiplexing schemes are compared. One particular frequency-domain multiplexing circuit, being developed for the XEUS space mission, is reviewed in more detail. The design issues related with dynamic range, bandwidth and noise folding are discussed.

INTRODUCTION

Superconducting transition edge sensors (TESes) have proven their capability as single-pixel X-ray and sub-mm detectrors in the recent years. The electrothermal feedback which arises when the TESes are voltage-biased eases their use by making the devices stable and by increasing the dynamic range and speeding up the response. As the output signal is current, a dc SQUID ammeter is a particularly attractive preamplifier owing to its cryogenic operation, low noise and small dissipation.

The new trend is towards imaging arrays of microcalorimeters, one particular application being spectroscopic X-ray imagers in astronomy [1,2]. Signals from separate pixels must then be distinguished from each other, either by spatial separation (separate wires for each pixel: direct readout), or separation in time (multiplexing). The direct readout setups are feasible, as evidenced by commercially available SQUID-based magnetoencephalography devices, but tend to be complicated and fragile. This is especially true in applications requiring sub-kelvin temperatures where low heat leakage is imperative. Only a low bandwidth is required for each wire, however, so that manufacturability and noise generation rather than the bandwidth requirement dictate the wire resistivity.

MULTIPLEXING

In multiplexing schemes, signals are multiplied by an orthogonal set of modulating functions $f_1(t), f_2(t)$ …, which act as fingerprints, and summed into a single wire. The signals are recovered when the summed signal is multiplied by the modulating functions again and low-pass filtered. Three choices for functions are shown in fig. 1, constituting frequency multiplexing (fig. 1b), Hadamard code multiplexing (fig. 1a) [3], and the basic time multiplexing (fig. 1c).

After a signal is fingerprinted by a modulator, wideband noise typically adds to it. In the summing node the parts of noise that fold to adjacent frequencies/codes/ timeslots degrading the SNR of the total system if precautions are not taken. Two alternatives are (i) to provide gain to the modulated signal in the signal path before the noise is added, and (ii) to provide a 'blocker' before the summing node to sieve away the parts of noise that would leak to adjacent channels. A timeslot- and code-preferring 'blockers' require active devices and external clock references for their realization, but a frequency-preferring 'blockers' can be simple passive LC-filters.

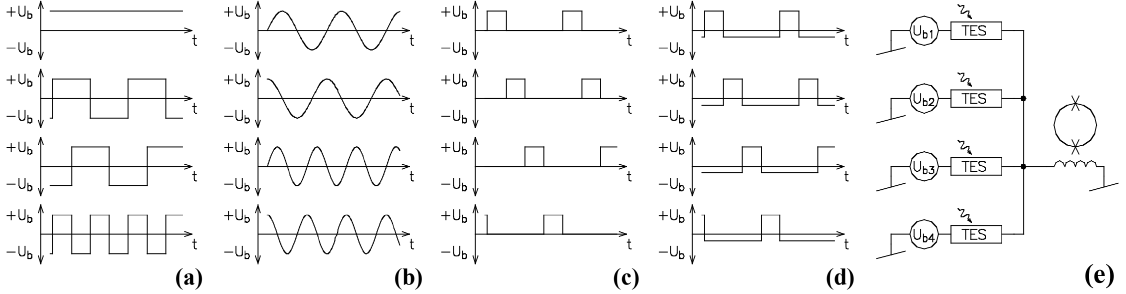

Figure 1. Modulating functions for Hadamard coding (a), frequency multiplexing utilizing both *sin* and *cos* quadratures (b), basic time multiplexing (c), and modified time multiplexing for improved duty cycle (d). The TESes are used as modulators (e), but SQUIDs can be used as well.

TES as a modulator

There are two active elements present already in the single-pixel circuit, which are capable to perform modulation: the TES and the SQUID. The TES, obeying Ohm's law would multiply perfectly the bias voltage carrying the modulating function, with the conductance G carrying the signal, into $I(t) = G(t)U_b(t)$. Such an approach has been taken in refs. [4,5]. Alternatively, one can utilize the inductance rather than conductance of the TES [8].

Two possible sources for nonlinearity in this process are the thermal effects and the magnetic effects. Thermal effects are suppressed by the thermal time constant of the TES, provided that lowest frequencies in the modulating function are significantly above the thermal roll-off frequency. The magnetic response (see fig.2) is fast, but typical operating currents are a small fraction of the magnetic critical current[1] and the effect is expected to be small.

If TES output currents are simply added as in fig.1e, Johnson noises from adjacent channels add, degrading the SNR. In principle one could move from voltage-like to current-like biasing, and utilize the capability of TES to provide power gain[2]

$$\frac{\Delta P_{out}}{\Delta P_{in}} = \frac{1}{2}\frac{(1-\beta)\alpha}{T/(T-T_b)-\alpha\beta} \qquad (1)$$

to increase signal and phonon noise levels, so that phonon noise dominates even when Johnson noises are added. In this case, the sacrificed dynamic range could be restored by additional negative feedback from subsequent amplifier stages.

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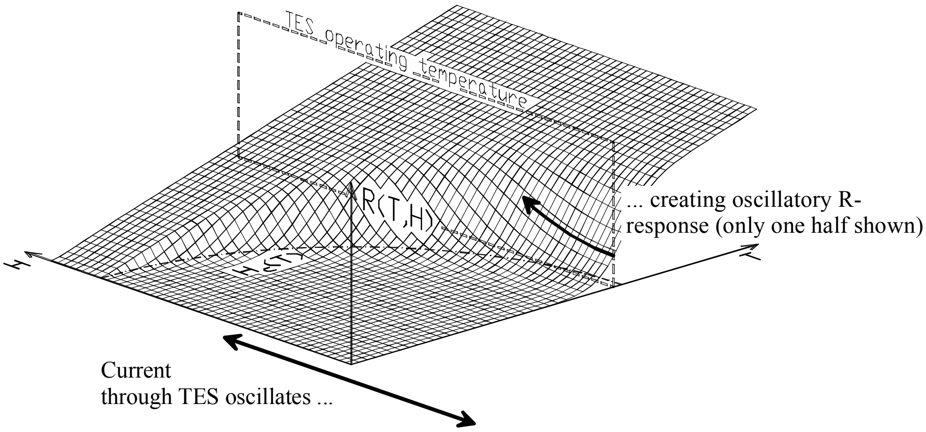
[1] The critical current encountered in practical TESes is set by flux-creep induced heating rather than the Ginzburg-Landau critical field (Arttu Luukanen, private communication).

[2] T is the film temperature, T_b is bath temperature, $\alpha = T/R\ dR/dT$ describes the transition steepness and the feedback parameter $\beta = (R-Rb)/(R+Rb)$ is expressed in terms of film and bias source resistances. At true voltage bias β=1 and at current bias β=-1.

A simpler alternative is to add noise-blockers in series with the TESes. With frequency multiplexing the blockers are just LC series resonators. With time multiplexing one could use TESes themselves as (limited) noise blockers by driving the passive TESes well above transition by applied magnetic field.



... creating oscillatory R-response (only one half shown)

Current through TES oscillates ...

Figure 2. Ginzburg-Landau resistance of a superconducting film as a function of temperature and applied magnetic field. AC current signal through the film causes a fast magnetically-induced response in the film resistance, when the film is biased into the transition region.

SQUID as a modulator

Signals from a group of dc-biased TES can be fed to a group of SQUIDs, whose biases act as modulating functions. Because dependence of the SQUID gain $\partial V/\partial \Phi$ on the bias current is a strongly nonlinear function these schemes are simplest with two-level functions, such as Hadamard and TD multiplexing. A disadvantage, however, is the need for one SQUID per each pixel. It is also technologically difficult to implement TESes and SQUIDs on the same chip, so that the complex TES-SQUID wiring may become a problem. Use of SQUID as a modulator with time multiplexing is demonstrated in ref. [6].

DESIGN OF A FREQUENCY-MULTIPLEXED CIRCUIT: SOME ISSUES

We're designing a 32 × 32 –pixel TES multiplexer, suitable for the XEUS mission [2]. The preliminary schematics are shown in fig. 3. Frequency multiplexing utilizing TESes as modulators is used due to spectral efficiency, simplicity of the noise-blocking filter and simplicity of the TES-SQUID wiring. Frequency multiplexing also helps to avoid 1/f –noise of the amplifiers and facilitates use of transformers for impedance matching.

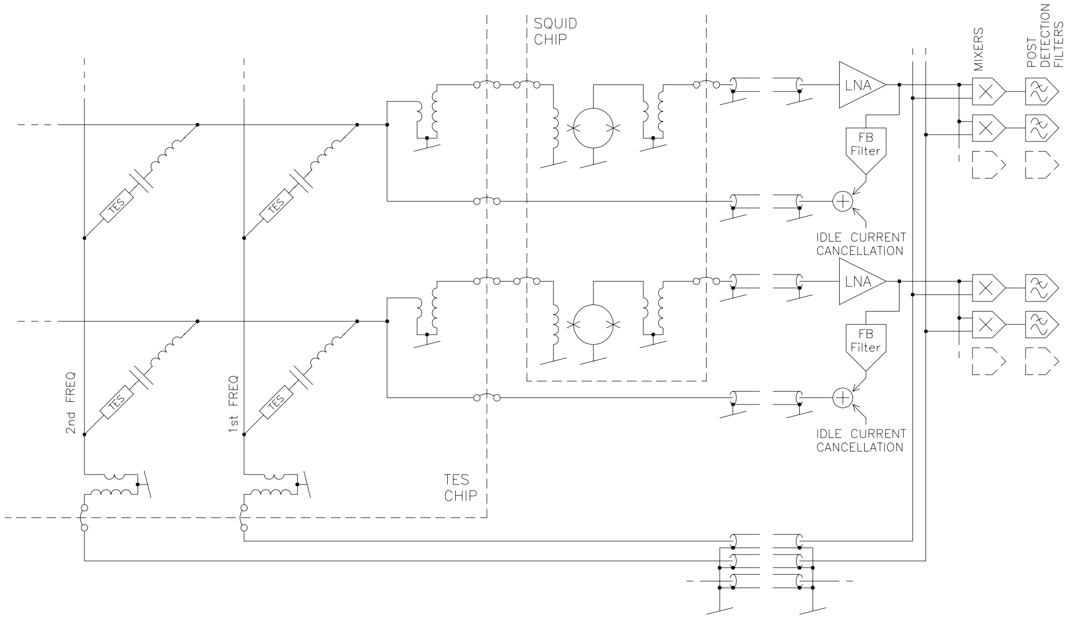


Figure 3. Simplified schematics for a frequency-multiplexed TES array.

Filter implementation

Thermal stability of the TES requires that the bandwidth of the series LC filter is at least 5.8 times the thermal cutoff frequency of the TES [7]. This sets $L \leqslant R/(5.8\ \omega_{th})$, or about 80 nH for our TESes with R = 10 mΩ. Such an inductor takes approximately 0.2 × 0.2 mm when implemented as a thin film coil on the TES chip.

The center frequency of the filters, i.e. the bias frequency, is limited from above at ~ 25 MHz by implementability of the thin-film capacitors. Upper limit is given by degradation of the noise temperature of the SQUIDs as a function of frequency.

The arrangement in fig. 3 allows one to adjust the set of frequencies fed to one row of pixels independently of frequencies fed to other rows. The bias power received by each TES pixel can thus be controlled independently, and the bias frequencies adjusted to accurately match the realized filter frequency.

The size of the filter array is determined by the coil-to-coil separation required for sufficiently low magnetic coupling. Magnetic coupling leads not only to crosstalk, but also reduction of the total bandwidth available to the 32 TESes which couple to a single SQUID. About 1 mm separation has been estimated to be sufficient in our case, which leads to a TES chip layout shown in fig. 4.

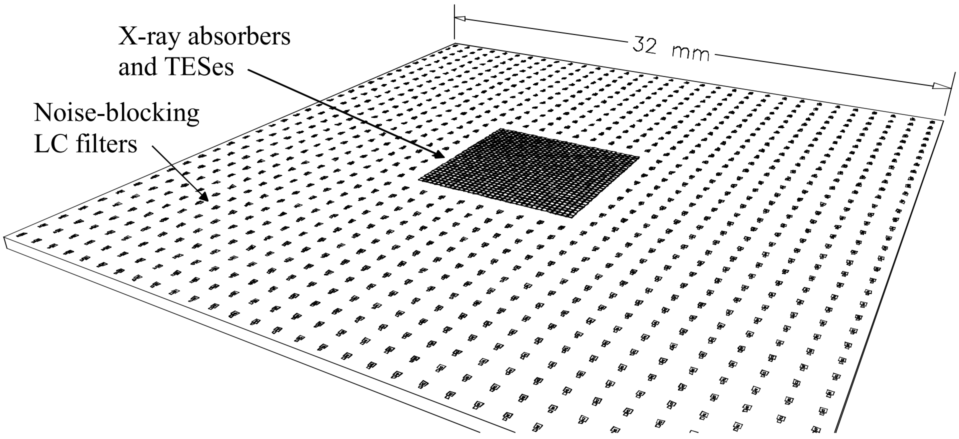


Figure 4: Relative sizes of the absorber array and the filter array on the TES chip.

The SQUID amplifier

The dynamic range of the current signal from a single ac-biased TES is [7],

$$\frac{I_{p-p}}{I_n}=\frac{2\sqrt{2}\times 2.36E_{\max}}{\Delta E_{FWHM}\sqrt{\tau_i}}, \tag{2}$$

$\approx 4.7\times 10^6$ at XEUS parameters $\Delta E_{FWHM}=2$ eV and $E_{max}=10$ keV. The TES thermal time constant determines the integration time τ_i ($\approx$ 50 μs for our TESes), if the LC filter settling time is chosen much shorter than that (the stability condition). It is possible to alleviate the need for dynamic range, however, by making the LC filter passband narrower than needed for stability so that the filter settling time effectively determines τ_i. A second filter would then be needed for each pixel, dimensioned to provide a stable bias impedance to the TES.

If the SQUID amplifier has a dynamic range at least three times eq. 2, we can reduce the SQUID contribution to 10% of the TES noise by adjusting the number of turns in the input coil, and still be able to survive the maximum signal. In practice more dynamic range than that may be needed, because of (i) chance of coincident signal from several TESes[3], and (ii) desire to keep full signal significantly below half flux-quantum to obtain more linearity.

Harmonics generated due to the SQUID nonlinearity by a single event end up above the active band and cause no harm. The idle ac current from a TES, present when no X-ray event takes place, has to be cancelled by summing an extra current with same frequency and amplitude but opposite phase. Mixing in the SQUID nonlinearity between an event-related current and imperfectly balanced idle currents is a source for spurious signals. We propose adaptive cancellation of the idle currents by a room-temperature controller, which traces the slow drifts in the circuit parameters, but doesn't react to fast X-ray events.

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[3] This is not likely at the XEUS-specified count rate of 4000 cps for the complete 32 × 32 array (100 cps per pixel), if TES pixels feeding a single SQUID are scattered randomly over the detector area. Pixels located close to each other are likely to give a lot of co-incident counts on point-like sources common in astronomy.

Open loop operation

Even in the impedance-matched case the SQUID noise is going to be dominated by the amplifier at and resistive cables to room temperature, sum of whose noise temperatures is assumed to be T_n = 40 K. The SQUID dynamic range cannot then be better than[4] [7]

$$\frac{I_{\max}}{I_n} = \frac{\Phi_0}{5.3 L_{SQ}^{3/4} C_j^{1/4} \sqrt{k_B T_n}}, \qquad (3)$$

which would lead to small SQUID dimensions in the edge of manufacturability, if sufficient dynamic range for the TES readout is desired. A second SQUID amplifier stage or use of local feedback within the cryogenic stage wouldn't change the situation, because the dominant noise source is outside the feedback loop.

A 5-SQUID series array with L_{sq} = 4 pH and C_j = 0.5 pF, having $\sqrt{5}$ times the dynamic range of a single SQUID, would sufficient if theoretical noise performance could be reached and no linearization was needed.

Flux-locked loop

Dynamic range can be increased when a (semiconductor) amplifier with a large open-loop dynamic range is included within the feedback loop. Closing the loop at the 25 MHz carrier frequency through room temperature is not feasible because the round-trip delay in the cables is too long. It is conceivable, however, to create a short-cable feedback loop through a semiconductor amplifier at the 20 K stage of the XEUS cryostat, where moderate cooling power of 250 mW is available.

An alternative is to utilize the fact that the carrier signal is deterministic: only its modulating envelope changes and needs to be fed back. Thus it is possible to use feedback through room temperature electronics at baseband frequency rather than carrier frequency. The total delay in the feedback loop should then be adjusted to correspond to an integer multiple of wavelengths at the carrier frequency.

REFERENCES

1. http://constellation.gsfc.nasa.gov/docs/science/staudience.html
2. http://sci.esa.int/home/xeus/index.cfm; ESA publications SP-1238, SP-1242 and BR-166, the European Space Agency (2000).
3. B. S. Karasik and W. R. McGrath, presentation at *the 12th International Symposium on Space THz Technology, Shelter Island San Diego, CA, February 14-16, 2001.*
4. J. Yoon et al, "Single superconducting quantum interference device multiplexer for arrays of low-temperature sensors", *Appl. Phys. Lett.* **78**, pp. 371-373 (2001).
5. T. Miyazaki, *PhD thesis,* ISAS / Univ. Tokyo (2001).
6. J. A. Chevrenak et al, "Superconducting multiplexer for arrays of transition edge sensors", *Appl. Phys. Lett.* **74**, pp. 4043-4045 (1999).
7. The SRON/VTT trade-off report "Readout concepts for an array of microcalorimeters for XEUS", unpublished (2001).
8. H. Seppä, "Superconducting transition edge bolometer in resistive and inductive mode", *IEEE Tran. Appl. Supercond.* **11**, pp. 759-761 (2001).

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[4] L_{sq} is the SQUID loop inductance, C_j is the junction capacitance, Φ_0 is the flux quantum and k_B is the Bolzmann constant.